Propagation and Ambient Noise Studies for Ocean Acoustics Applications

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LONG-TERM GOALS

The objectives of this research is to study the ocean ambient noise field in the 0.1-50 kHz frequency band to determine ways to exploit noise for environmental characterization and to improve sonar system performance.

OBJECTIVES

Basic research on ocean ambient noise has led to several potential applications for the Navy. In recent work we have developed a new type of passive sensor that uses ocean noise to glean information about the seabed properties without using a sound projector or explosive [1]. The value and impact of these techniques could be significant and we are investigating various ways to take advantage of the noise field. The passive nature of noise based processing is appealing in situations where sound sources are not desired (e.g. due to environmental restrictions). Further, the measurements are relatively simple compared to using conventional methods which require one (possibly two) research ship(s) as well as specialized sources and/or sonar systems (e.g. chirp sonar). While the noise processing techniques are a powerful tool for passive seabed-characterization, we are just beginning to understand how these methods work as well and the limitations.

APPROACH

The processing approach is based on the cross-correlation between the surface noise generated by breaking waves, and the echo return from the seabed. We refer to this as passive fathometer processing. Except at lower frequencies dominated by shipping, breaking waves commonly are the predominant source of ambient noise. It is important to note that the passive fathometer processing is coherent which is essential to preserve the travel times to the seabed and layers beneath. One of the differences between the passive fathometer applications and other coherent noise processing is the use of beamforming to focus the received energy on the useful noise and reduce interference from unwanted noise sources. This has the effect of improving the estimates for seabed layering while reducing the needed averaging time.

In the original formulation [1], conventional beamforming was used but improvements have been made using adaptive beamforming methods. We use adaptive methods to suppress the noise energy coming from directions other than that of interest (i.e., directly above and below the array). In this case

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14. ABSTRACT
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15. SUBJECT TERMS

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there is significant energy coming near horizontal that is of no interest for the passive fathometer processing. To adaptively beamform, the Minimum Variance Distortionless Response (MVDR) steering weight vector $\mathbf{w_A}$ at frequency ω are computed according to,

$$\mathbf{w_A} = \frac{\mathbf{K}^{-1}\mathbf{w}}{\mathbf{w}'\mathbf{K}^{-1}\mathbf{w}}, \tag{1}$$

where **K** is the data cross-spectral density matrix (CSDM), the weight **w** is the conventional plane-wave steering vector at 90 degrees (for each hydrophone in the array) $\mathbf{w} = [w_1, w_2, \ldots w_M]$, for hydrophone *m* is, $w_m = e^{im\Delta k}$ and $k = \omega / c$ with Δ being the design half-wavelength spacing and *c* the sound speed ($\mathbf{w}'$ is the conjugate transpose of the vector). For conventional beamforming the upward looking beam is just the conjugate of the downward looking beam. Assuming the same is true for MVDR, the passive fathometer correlation at frequency ω is given by the expression,

$$C_{\mathbf{A}} = \mathbf{w}'_{\mathbf{A}}\mathbf{K}\mathbf{w}^{*}_{\mathbf{A}} \tag{2}$$

However, this expression is only approximate since for adaptive methods the upward and downward steering weights are not necessarily conjugates of each other. An improved result can be obtained using,

$$C_{A} = \mathbf{w}'_{-A}\mathbf{K}\mathbf{w}_{+A} \tag{3}$$

Where $\mathbf{w}_{+A}$ is the up-looking adaptive steering weight and $\mathbf{w}_{-A}$ is the down-looking adaptive weight. The time-series passive fathometer response is simply the inverse Fourier Transform of $C_A(\omega)$ or, $c(t) = F^{-1}\{C_A(\omega)\}$.

Since MVDR processing involves inverting the CSDM, problems can occur when the matrix is less than full rank. To stabilize the inversion, the MVDR weights are recast with diagonal loading,

$$\mathbf{w}_{A} = \frac{[\mathbf{K} + \varepsilon\mathbf{I}]^{-1}\mathbf{w}}{\mathbf{w}'[\mathbf{K} + \varepsilon\mathbf{I}]^{-1}\mathbf{w}} \tag{4}$$

where **I** is the identity matrix and the ε parameter is the adjustable diagonal loading strength. The diagonal loading is equivalent to adding white noise with its power depending on the strength parameter, ε.

The MVDR processor is also known to be sensitive to mismatch. For example, this mismatch can come in the form of environmental factors (such as non-planewave propagation) or the actual array shape being different from the assumed shape. The White Noise Gain Constraint (WNC) beamformer adjusts ε for each angle to provide robustness to the adaptive processor which is constrained by the white noise gain. The WNC beamformer can be tuned to be pure conventional, pure MVDR or somewhere in between according to the white noise gain (WNG) given by,

$$\mathrm{WNG} = 10\log\left(\frac{\delta^2}{M}\right) \le 0 \text{ dB}$$

where M is the number of hydrophones and δ is given by,

$$\delta^2 = \left| \mathbf{w}'_A \, \mathbf{w}_A \right|^{-1} < M$$

When the WNG = 0 dB the WNC beamformer corresponds to the conventional beamformer while for WNG = $-\infty$ the WNC beamformer corresponds to MVDR. In typical sonar processing (e.g. detecting weak targets), WNG = -2 dB gives a reasonable compromise between conventional and MVDR processing. However, for passive fathometer processing, a more typical value is WNG = -10 dB.

WORK COMPLETED

For the adaptive passive fathometer processing, several existing data sets were analyzed to determine the improvements possible and are documented in publication [1]. Two moored arrays were analyzed, one from data collected near Sicily and the other from an experiment in Dabob Bay. The Dabob Bay results are shown in the results section (and in publication [1]). In addition, two drifting array data sets were analyzed and summarized in the results section (details are in publication [1]).

RESULTS

The Dabob Bay experiment was in October 2007. A moored vertical array was deployed in approximately 185 m water depth and noise was collected on a 16 hydrophone array (50-1500 Hz band with 0.5 m hydrophone spacing). The Dabob adaptive passive fathometer results are shown in Fig. 1. The top panel of Fig.1 shows the echo returns in two-way travel times. The lower plot is a sub-bottom profile taken with a Knudson 320B system that was on the *R/V* New Horizon. active sub-bottom profiling system. The echo returns from the adaptive passive fathometer processing are consistent with the active sonar system.

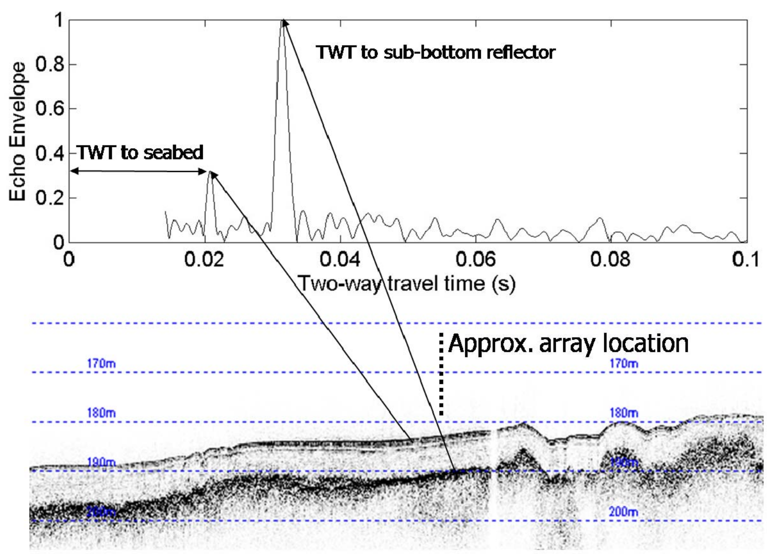

Figure 1: Bottom echoes from passive fathometer processing of ambient noise data. Top panel shows the bottom echoes and lower panel shows the sub-bottom profile taken with an active Knudson sub-bottom profiler sonar. The returns from the noise processing in the top panel are in good agreement with the active sonar results in the lower panel.

The short two way travel time (TWT) from the array to the seabed (about 0.02 s) is because the array was moored close to the seabed (about 7.5 m from the bottom hydrophone to the seabed). The passive fathometer return shows a relatively weak arrival at the water-seabed interface at about 0.02 s TWT with a much stronger return at around 0.03 s. This stronger second return suggests a higher impedance contrast for the second interface. This also is suggested in the sub-bottom profile.

For comparison, adaptive and conventional passive fathometer processing results are shown in Fig. 2. The conventional processing shows higher unwanted noise levels especially just past the second peak (at around 0.03 s).

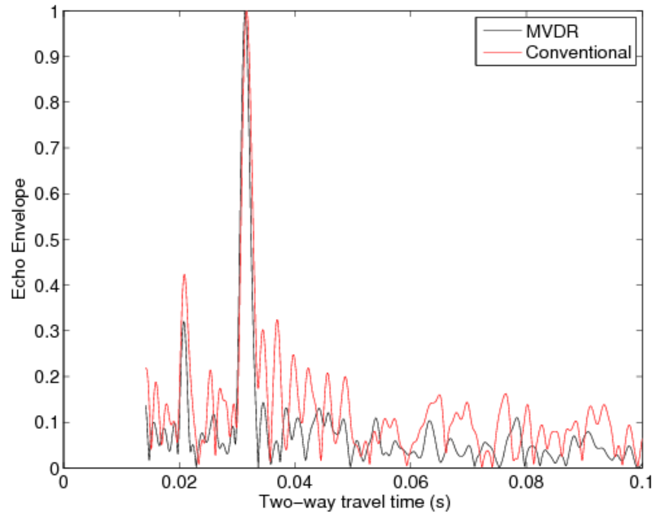

Figure 2: Comparison between conventional passive fathometer processing (red) and adaptive (black) for the Dabob Bay experiment. The red line with conventional processing shows a significantly higher unwanted noise level in the echo return than for adaptive.

Additional analysis can be made from data taken from the drifting array data sets. This is the same data set as was used for conventional processing in Reference [1] (i.e. the NATO Undersea Research Centre's Boundary 2003 experiment) and is analyzed here with adaptive methods. The drifting array has 32 hydrophones spaced at 0.18 m (design frequency of 4.2 kHz). The depth of the reference hydrophone was approximately 73.5 m. The wind varied during the experiment but was, on average, about 15 knots. In this case, the moving array limits the number of snapshots that can be taken per time trace and here, snapshots were averaged over 90 s to form the CSDM. The adaptive processing parameters for this data were as follows: frequency band 50-4000 Hz, snapshot size T_{snap} = 1.4 s, total averaging time T_{ave} = 90 s. For the conventional processing the same parameters were used. However, the frequency band was reduced to 200-4000 Hz because of significant shipping noise below 200 Hz that cannot be suppressed using the conventional approach.

The data were analyzed to understand the improvements provided using adaptive processing. In Fig. 3, the adaptive beampatterns are shown in the 1000-1010 Hz band as a function of record number as the array drifts. The horizontal axis is the record number which corresponds to range as the array drifts and the vertical axis is the grazing angle. The top panel in Fig. 3 is the down-looking beampattern and the bottom panel is up-looking beampattern. The up-looking and down-looking beampatterns are quite distinct. Recall that only directly up and down steering directions are used for the passive fathometer processing. Note the regions near horizontal grazing angle in both panels of that are 30-40 dB down

where the adaptive processor tries to null the beamformer response.   In addition, the top panel shows the suppression of the high intensity beams above horizontal (traveling downward). Anything not coming from straight up or straight down is treated as interference so improvement is achieved by suppressing the interference. Shown in the far right of Fig. 3 (small vertical bars) is the conventional beampatterns for comparison. Contrary to adaptive processing where the beampatterns change with time the conventional beampatterns is fixed so only a single plot is needed. Note the sinc-like pattern for conventional beamforming has much less suppression of the interferers near horizontal.

In Fig. 4, the adaptive and conventional beampatterns are shown in polar coordinate for the same 1000-1010 Hz band for the up- and down- looking beams used in the passive fathometer. The adaptive beampatterns are from the record number 250 which is shown with a vertical black line in Fig. 3. The adaptive beampatterns display a sidelobe structure that is quite different from the conventional ones and also have narrower beams.

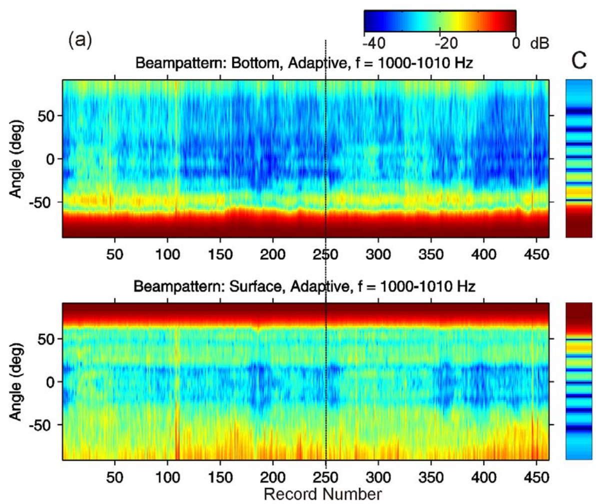

Figure 3: Data from drifting array in the 1000-1010 Hz band. Down-looking (top panel) and up-looking (bottom panel) beampatterns for the adaptive processing as a function of record number as the array drifts. Conventional beampatterns are constant and are shown as the small vertical bars on the right (labeled C).

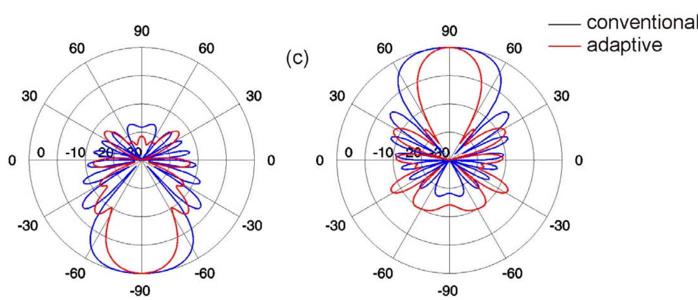

Figure 4: Adaptive and conventional polar beampatterns for the 1000-1010 Hz band for the down- and up-looking beams used in the passive fathometer for record number 250 (shown as a black line in Fig. 3).The adaptive beampatterns shown in red are narrower in the up and down looking directions and have more suppression of unwanted noise than the conventional beampattern results (blue).

IMPACT/APPLICATIONS

This work may have a significant impact on several Navy sonar systems (e.g., ASW, MCM, underwater acoustic communications). Knowing the seabed properties will improve at-sea situational awareness by being able to accurately predict acoustic propagation. And, because this is a passive method it can be designed into a system used for covert activities, low power applications and can be used even in environmentally restricted areas.

TRANSITIONS

Results of this research are being developed under the Ocean Bottom Characterization Initiative (PMW-120). This involves developing an sensor (over the next several years) that is based on techniques described here and will initially be deployed by the Naval Oceanographic Office.

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HONORS/AWARDS/PRIZES

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